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Fast Iterative Technique for the Calculation of Frequency Dependent Gain in Excimer Laser Amplifiers

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Introduction

The motivation in initiating these calculations is to allow us to observe the frequency evolution of a laser pulse as it propagates through an amplifier and then through a sequence of amplifiers. The question we seek to answer is what pulse shape do we need to produce out of a front-end oscillator so that after it propagates through the whole Aurora KrF fusion amplifier chain will result in high energy, broad-band laser fields of a given bandwidth that can be focussed onto a fusion target.

The propagation of single frequency source through an amplifier with distributed loss was considered by Rigrod [1] and was significantly expanded by Hunter and Hunter [2]. The latter included amplified spontaneous emission [ASE] considerations both in the direction of and transverse to the coherent field. Analytic solutions that include forward and backward prapagating fields and ASE were derived which were transcendental in nature but allowed for fairly easy computer calculations. Transverse ASE were calculated using the saturated gain resulting from longitudinal fields and were used to compare this with the longitudinal fields. Thus, the influence of the transverse ASE were not folded back into the longitudinal field equations. Large computer programs are now available at LANL [3] which include the influence of transverse ASE on the longitudinal fields. However, none of these considerations have worried about the changes in the frequency characteristics of the propagating field or of how each of the frequency field components contributes to the saturation of the gain. The inclusion of full frequency characteristics to the analytic solutions of Hunter and Hunter [2] proved impossible at least for this author and a new calculational technique was developed and is the subject of this talk.

Longitudinal Field Equations

We will assume steady-state conditions in the derivations and thus the equations are not for ultra-short pulse applications. Writing the rate equation for the upper state density, we have

$$N_B(x)=[F_B/(Q_B+A_B)]\{1+\int [I_+(\nu',x)+I_-(\nu',x)+I_{A+}(\nu',x)+I_{A-}(\nu',x)]/I_s(\nu')d\nu'\}^{-1} \qquad (1)$$

$I_+(\nu',x)$ and $I_-(\nu',x)$ are the laser field intensities going in the $+x$ and $-x$ directions, respectively at x with frequency ν'. Similarly I_{A+} and I_{A-} are the amplified spontaneous emission fields. $I_s(\nu)$ is the saturation intensity at ν and is related to the stimulated emission cross-section $\sigma_{st}(\nu)$ at frequency ν. F_B is the upper state formation rate, A_B is the upper state radiative lifetime and Q_B is the total upper state quenching rate. We can show that $F_B/[Q_A+A_B]$ is related to the gain and the stimulated emission cross-section so that

$$F_B/[Q_A+A_B]=g_o(\nu)/\sigma_{st}(\nu)=g_o(\nu_o)/\sigma_{st}(\nu_o) \qquad (2)$$

where ν_o is the frequency of line-center. The stimulated emission cross-section is calculated following Brau [4] as

$$\sigma_{st}(\nu_o)=(1/4\pi)(\ln 2/\pi)(\lambda^4/c\Delta\lambda)A_B \qquad (3)$$

with $\Delta\lambda$ the full-width at half-maximum bandwidth. Assuming a Lorentzian bandwidth for the fluorescence profile, we write

$$\sigma_{st}(\nu)/\sigma_{st}(\nu_0)=(\Delta\nu/2)^2/[(\nu-\nu_0)^2+(\Delta\nu/2)^2] \tag{4}$$

One writes the field equations as follows

$$\begin{aligned} dI_{\pm}(\nu,x)/dx = &\pm(\sigma_{st}(\nu)/\sigma_{st}(\nu_0))g_0(\nu_0)I_{\pm}(\nu,x) \\ &*\{1+\int [I_+(\nu',x)+I_-(\nu',x)+I_{A+}(\nu',x) \\ &+I_{A-}(\nu',x)]/I_s(\nu')d\nu'\}^{-1} \mp \alpha I_{\pm}(\nu,x) \end{aligned} \tag{5}$$

and for the longitudinal ASE fields

$$\begin{aligned} dI_{A\pm}(\nu,x)/dx = &\pm(\sigma_{st}(\nu)/\sigma_{st}(\nu_0))g_0(\nu_0)I_{A\pm}(\nu,x) \\ &*\{1+\int [I_+(\nu',x)+I_-(\nu',x)+I_{A+}(\nu',x) \\ &+I_{A-}(\nu',x)]/I_s(\nu')d\nu'\}^{-1} \mp \alpha I_{A\pm}(\nu,x) \\ &+A(\nu,x)(g_0(\nu_0)/\sigma_{st}(\nu_0))*\{1+\int [I_+(\nu',x) \\ &+I_-(\nu',x)+I_{A+}(\nu',x)+I_{A-}(\nu',x)]/I_s(\nu')d\nu'\}^{-1} \end{aligned} \tag{6}$$

α is the unsaturated loss coefficient. $A(\nu,x)$ is the spontaneous emission source term with frequency ν at location x in the presence of driven and ASE fields. We can treat its contribution to the logitudinal ASE by using a geometric solid angle factor which depends on its location in the gain media.

A self-consistent field iterative mehod

As described in the introduction the above set of equations including the full frequency spectrum of the propagating fields does not easily lend itself to an analytic solution. We wish to describe here a technique which should be applicable to any problem in which the quantity to be determined itself acts on parameters that determine that quantity. These nonlinear problems, especially if they lead to saturation, is very amenable to a self-consistent field iterative method. Indeed, the problem of frequency dependent gain propagating through amplifiers for both single and double pass configurations without ASE are done rapidly with IBM PC computers with programing size limited by DOS to 640 KBytes.

The technique involves calculating the fields in the amplifier in a first guess. Then the initial input fields are send through the system using the previously calculated fields. The third iteration sends through the gain medium the initial input fields using the saturating fields of the second iteration. This process is continued until the change in the calculated fields is smaller than a preset accuracy and the program ends. To give a rough argument of why this works, consider the single-pass field propagation through a gain medium. If we simply calculate the field through the amplifier without puting in saturation of the gain due to the field, the field calculations will surely come out too large. The second iteration using this too large field for the gain saturation will give resultant fields which are too small. We see that as each iteration proceeds we will get closer and closer to the true answer. The difficulty computationally is that if the guess is too far off we can oscillate in value ouside the range of the computer. Thus, to insure that the calculation converge and that it does so in the least number of iterations we should try to make as accurate a first guess as possible. For the single pass amplifier we make the first guess at location x by using the field at location $x-\Delta x$ as follows:

$$\Delta I_{n+}(\nu,x_k)=[(\sigma_{st}(\nu)/\sigma_{st}(\nu_0))g_0(\nu_0)\{I_{n+}(\nu,x_{k-1})$$
$$*\{1+\int [I_{n-1+}(\nu',x_k)/I_s(\nu')]d\nu'\}^{-1}$$
$$-\alpha I_{n+}(\nu,x_{k-1})] \quad (7)$$

and

$$I_{n+}(\nu,x_k)=I_{n+}(\nu,x_{k-1}) + \Delta I_{n+}(\nu,x_k) \quad (8)$$

For the double pass amplifier calculations the initial guess of the fields in the amplifier is somewhat more complicated. This involved first calculating the backward field in the above manner assuming an initial field in the backward direction a few order of magnitudes higher than the forward input field. With this backward field we proceed as before with the initial guess on the forward field.

Results of Calculation

The following examples of results deal with single-pass and double pass propagation of frequency dependent fields through KrF amplifiers. In discharge devices the gain is very high with $g_0=.2\ cm^{-1}$ and the gain over unsaturated loss ratio $(g_0/\alpha)=20$. The laser parameters assumed are a full width half maximum medium gain bandwidth=400 cm^{-1} and a saturation intensity=2 Mw/cm^2. We use an input frequency field coming from an oscillator with an intracavity etalon of 50% reflectivity and 200 cm^{-1} mode separation [5]. The total energy out of the oscillator is .846 mJ with a pulse length of 30 ns. This input field is shown in Fig. 1 and is used for the calculations in the examples for discharge devices and we use an input energy of 8.46 mJ for the example using gain parameters appropriate for electron beam pumping. The frequency dependent output field in passing through a single-pass amplifier 100 cm long with the above gain parameters is shown in Fig. 2. The frequency integrated field development is shown in Fig. 3. Figure 4 gives the output field calculations at line center and at the peak of the input field as a function of the number of iterations until a self-consistent field is reached. For the double-pass configuration through the same amplifier the output field is shown in Fig. 5. The frequency integrated field development is shown in Fig 6. The number of iterations to convergence is shown in Fig 7. The initial guess for the fields in the amplifier is, however, much more sophisticated than for the single-pass case. We expect the number of iterations to convergence for the single-pass case would be somewhat reduced if the same technique for the double-pass initial field calculation is applied to it. Finally, we compare the calculations for an electron beam pumped laser with much lower gain parameters $g_0=.03\ cm^{-1}$ and $g_0/\alpha=7.5$. The double-pass output through such an amplifier is shown in Fig.8. The frequency integrated field is shown in Fig.9. Figure 10 gives the number of iterations to a self-consistent field convergence. Note that for lower gain situations the calculations are much simpler.

Discussion

The above calculations are performed on small personal computers. We have not included at present the effects of longitudinal ASE or the effects of saturable absorbers located within the gain linewidth of the laser transition. The latter has been shown to be experimentally [5] very important in limiting the wide bandwidth amplification for excimer fusion laser systems. We believe both of these effects can be included in the calculations and still use only small personal computers. The inclusion of transverse ASE, however, will require memory sizes much larger than that available for BASIC programs in DOS but should still be feasable on small personal computer systems using more sophisticated operating systems.

References

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5. R.C. Sze, S.J. Thomas, N.A. Kurnit and C.W. Patterson, "Wide bandwidth control studies for the advanced Aurora KrF fusion laser front end", Conference on Lasers and Electro-optics, paper CWF46, Anaheim, CA (May, 1990)

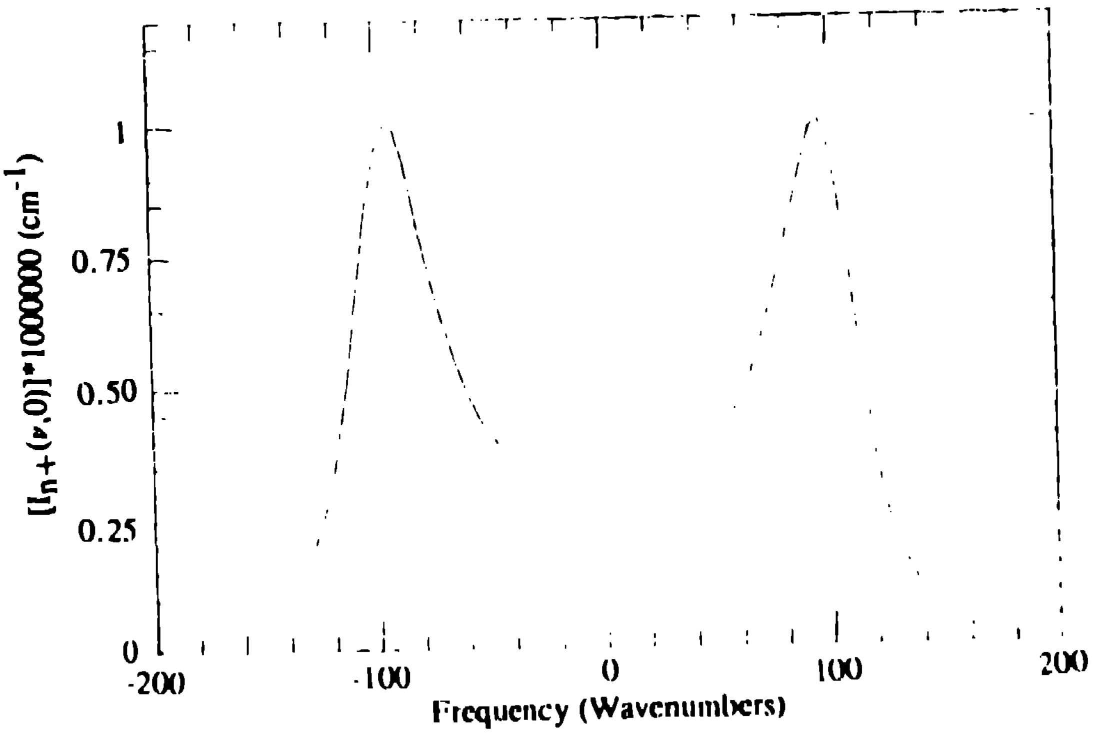

Figure 1. Frequency dependent input pulse into amplifier. .846 mJ for the discharge device amplifiers and 8.46 mJ for the electron beam pumped amplifiers. Pulse width is 30 ns.

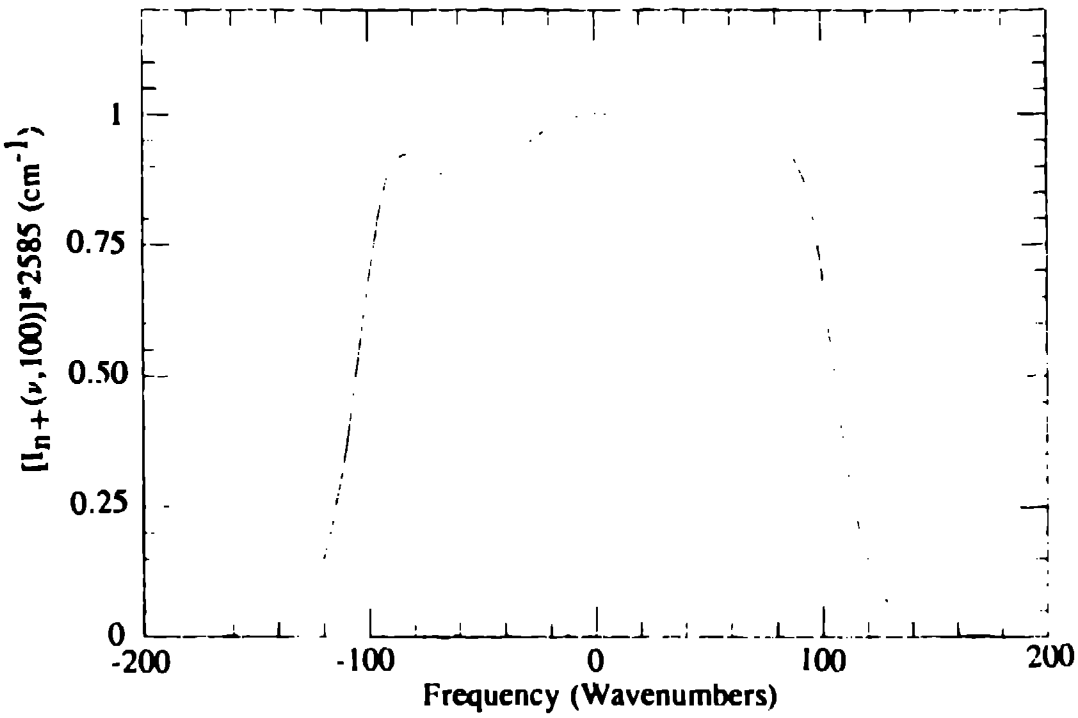

Figure 2. Frequency dependent single-pass output amplifier out of 100cm long KrF with $g_0=.2\ cm^{-1}$, $g_0/\alpha=20$.

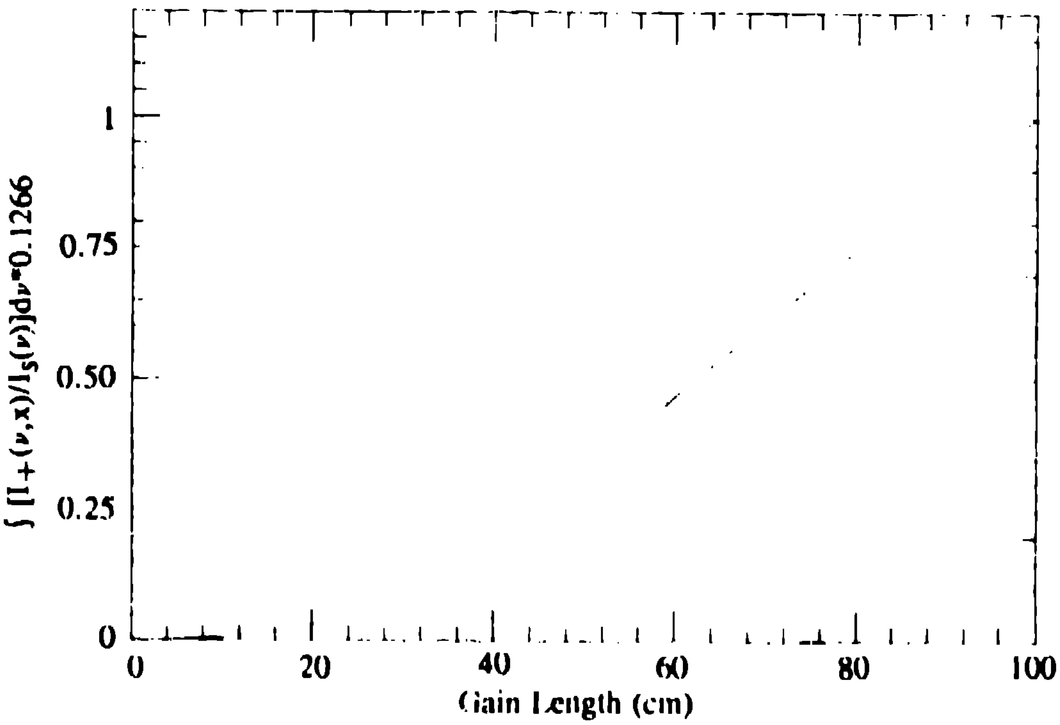

Figure 3. Integrated intensity as a function of gain length for single-pass amplifier of Fig.2.

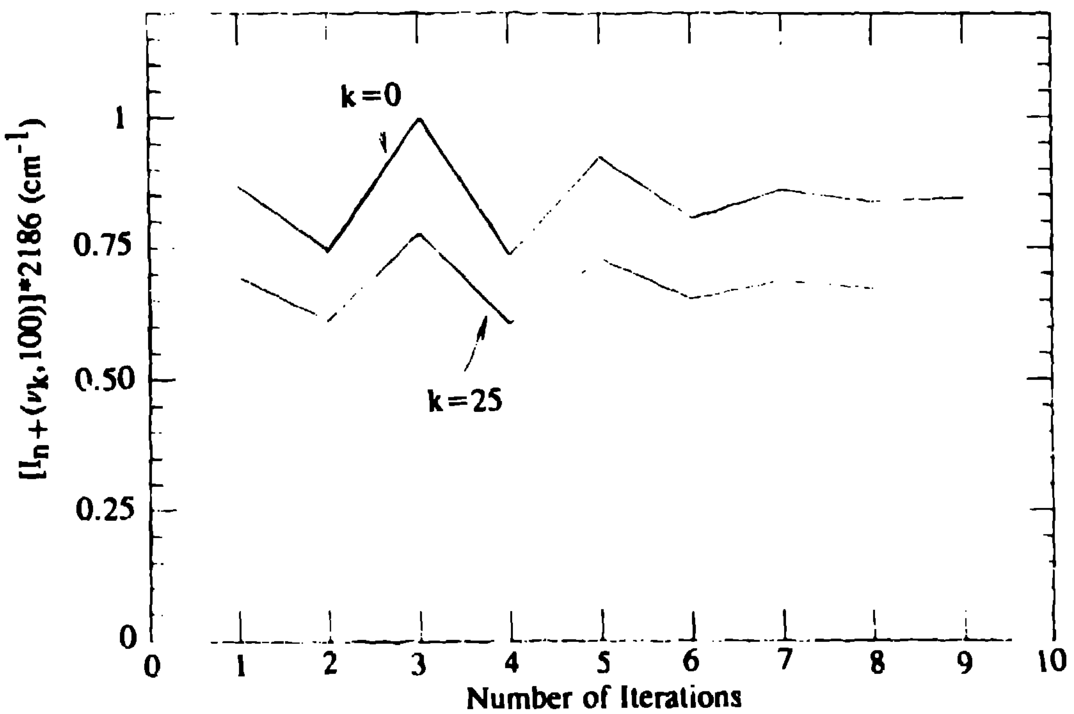

Figure 4. Field intensity at exit of amplifier. Values are at center frequency (k=0) and at initial peak intensity (k=25) as a function of number of iterations before a self-consistent field is achieved for parameters of Fig. 2.

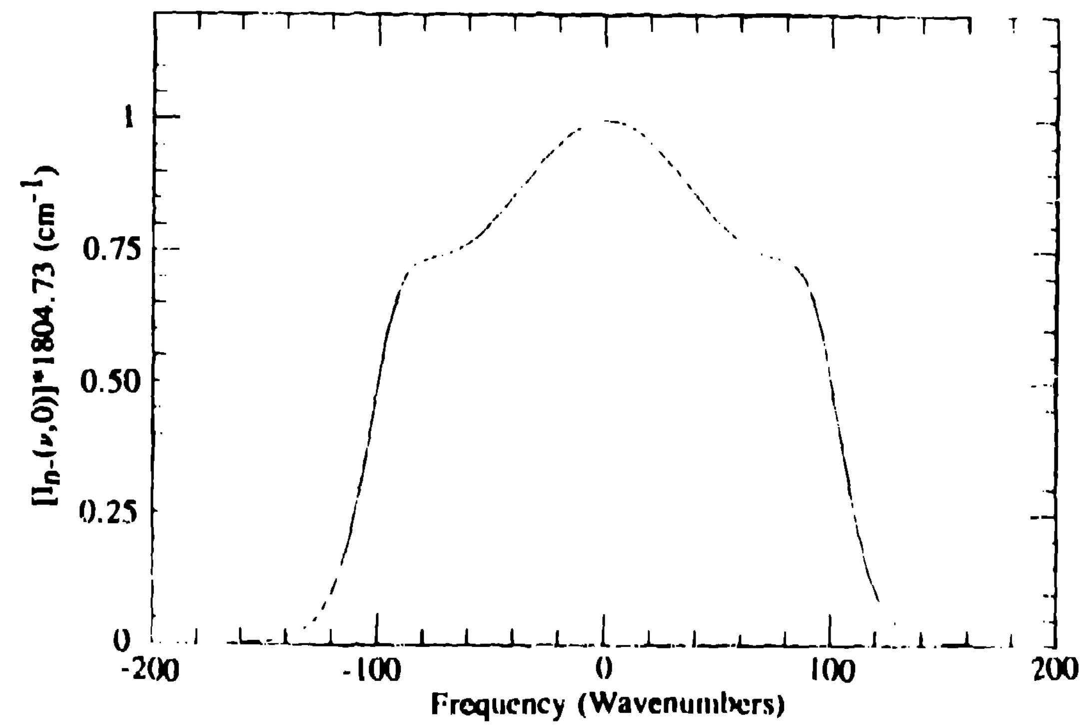

Figure 5. Frequency dependent double-pass output out of 100cm long KrF amplifier with $g_0=.2\ cm^{-1}$, $g_0/\alpha=20$.

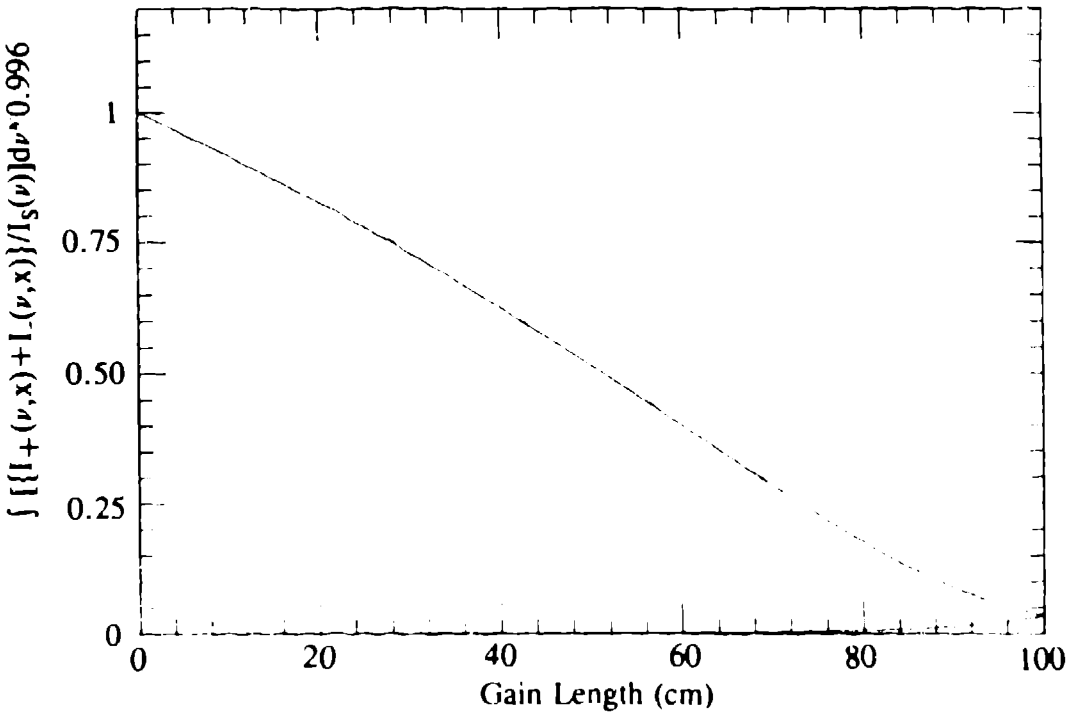

Figure 6. Integrated intensity as a function of gain length for double-pass amplifier of Fig.5

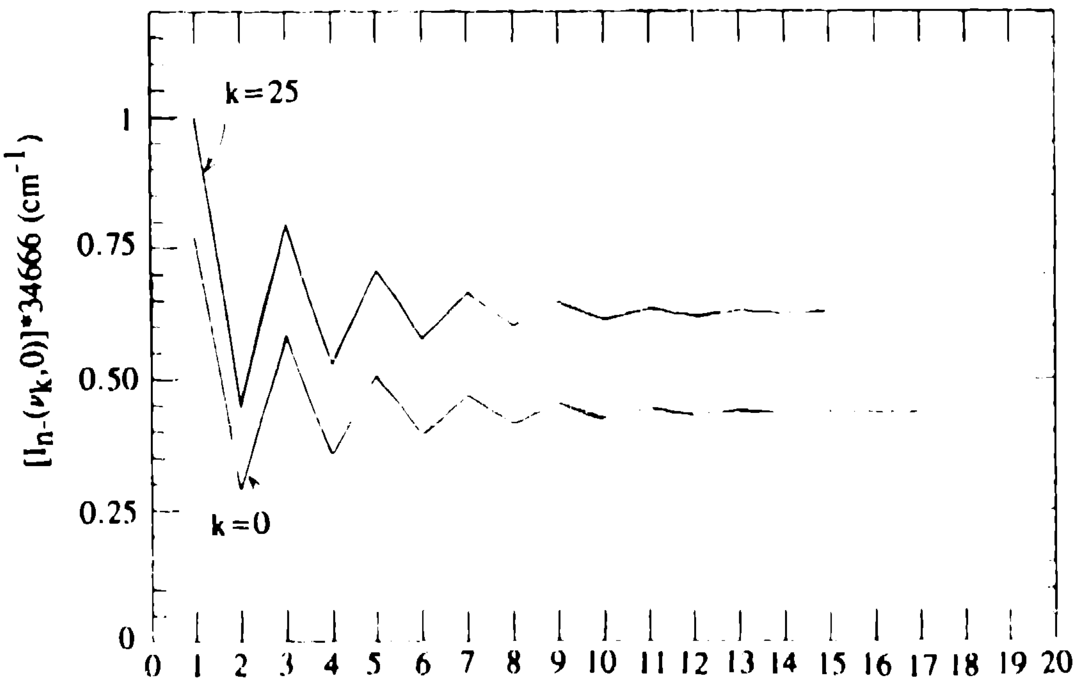

Figure 7. Field intensity at exit of amplifier. Values are at center frequency (k=0) and at initial peak intensity (k=25) as a function of number of iterations before a self-consistent field is achieved for parameters of Fig. 5.

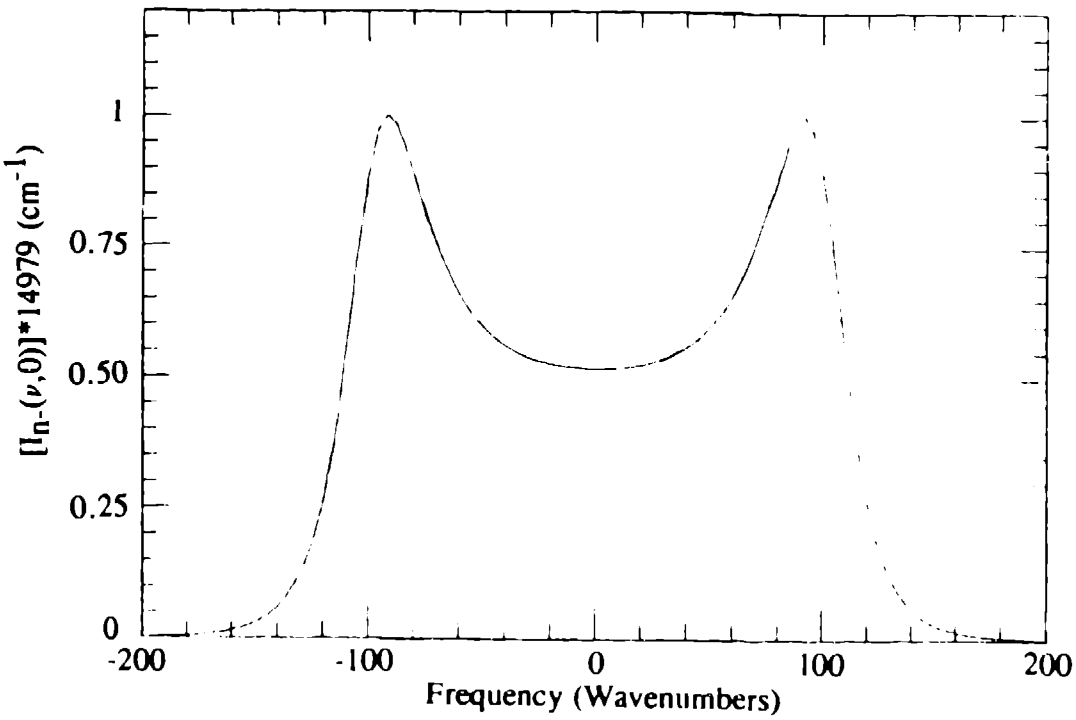

Figure 8. Frequency dependent double-pass output out of 100cm long KrF amplifier with g_o=.03 cm^{-1}, g_o/α=7.5.

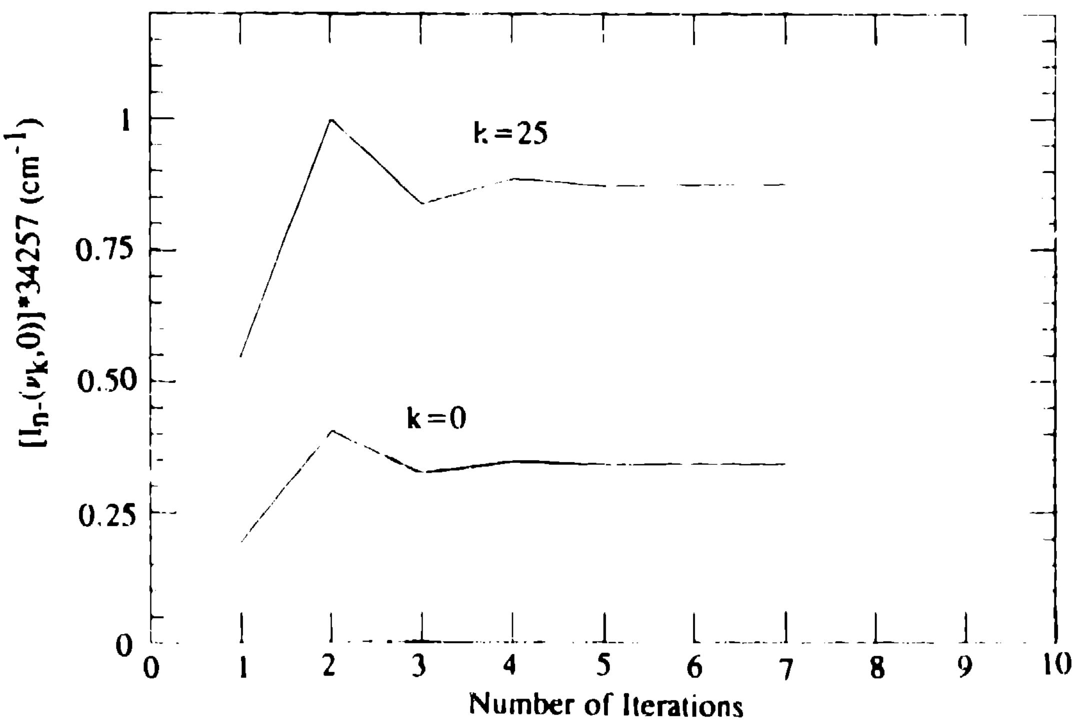

Figure 9. Integrated intensity as a function of gain length for double-pass amplifier of Fig.8

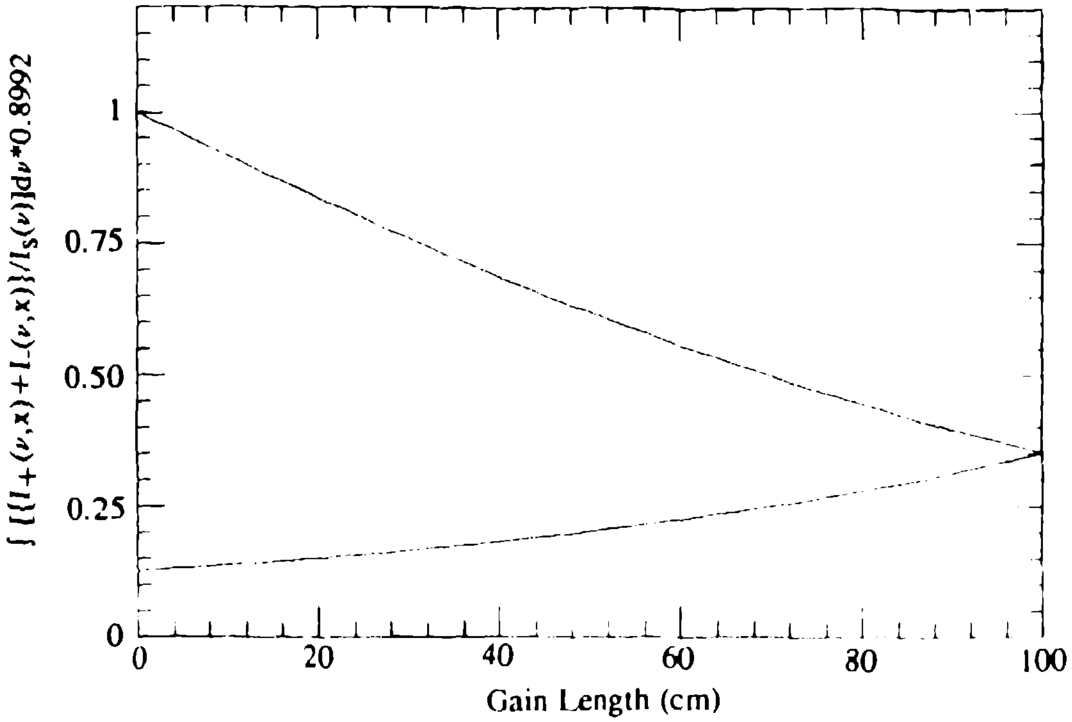

Figure 10. Field intensity at exit of amplifier. Values are at center frequency (k=0) and at initial peak intensity (k=25) as a function of number of iterations before a self-consistent field is achieved for parameters of Fig. 8.